Research and Innovation Action

Flex5Gware

Flexible and efficient hardware/software platforms for 5G network elements and devices

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Flex5Gware

WP1 – 5G Architecture requirements, specifications, and use cases

D1.2 – Flex5Gware performance evaluation

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V0.3	12/05/2017	Second round of inputs from KPI drivers, introduction and conclusion in place
V0.4	01/06/2017	Integrated document with most of the content already in place ready for internal review
V0.5	12/06/2017	Integration of comments from internal review and document ready for PMT review
V0.6	26/06/2017	Integration of comments from PMT review
V1.0	30/06/2017	Minor formatting and correction updates. Version ready for EC submission
V1.1	13/10/2017	Update based on the comments received at the EC review. PoC/WP references added to Table 3-21 (moved from Section 4 to Section 3) to highlight the fact that shown results correspond to building blocks developed within Flex5Gware and not to system-level validations.

Executive Summary

This deliverable presents an evaluation and summary of the Flex5Gware achievements with respect to target KPIs put forth in [Fle11]. These achievements result from the development carried out by partners in all the work packages, but most significantly based on the outcomes of the proof-of-concept (PoC) evaluation (WP6). As such, these developments consist of functionalities which have been integrated in the different proof-of-concepts and also of functionalities corresponding to the activities carried out within WP2, WP3, WP4, and WP5, that do not match a specific proof-of-concept, but that, nonetheless yield an improvement with respect to the State of the Art (SotA).

This way, while [Fle11] served as the reference for the performance assessment of the project, this deliverable constitutes its final evaluation, thus completing the last milestone to assess the progress of the scientific and technical activities. The results from this evaluation show a remarkable level of accomplishment with respect to the target objectives as it will be detailed throughout the document.

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List of Acronyms and Abbreviations

Term	Description
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
A/D	Analogue to Digital
ADC	Analogue Digital Converter
API	Application Programming Interface
BOM	Bill of Material
BW	Bandwidth
CMOS	Complementary Metal-Oxide-Semiconductor
CoMP	Coordinated Multipoint
CPS	Coupled Processing System
CRAN	Cloud RAN, Centralized RAN
CST	Cost
CV	Crowded Venue
DH	Dynamic Hotspot
DL	Down Link
DPd	Digital Pre-distortion
EU	European Union
FBMC	Filter Bank Multicarrier
FDD	Frequency Division Duplex
FPGA	Field Programmable Gate Array
FVR	Flexibility / Versatility / Reconfigurability
GUI	Graphical User Interface
HD	High Definition
HW	Hardware
IC	Integrated Circuit
IoT	Internet of Things
ISF	Integration / Size / Footprint
KPI	Key Performance Indicator
LAT	Latency
LDPC	Low Density Parity Check
LTE	Long Term Evolution
LTE-U	LTE Unlicensed
MAC	Media Access Control
MBV	Mobile Broadband in Vehicles
MDV	Mobile Data Volume
MIMO	Multiple Input Multiple Output
mmWave	Millimetre Wave
MTC	Machine Type Communication
MU-MIMO	Multi-user MIMO
NGMN	Next Generation Mobile Networks
NoU	Number of Users
NRG	Energy Efficiency
OBW	Operation Bandwidth

OPEX	Operating Expense
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PCB	Printed Circuit Board
PE	Performance Equipment
PHY	Physical Layer
PLL	Phase Locked Loop
PoC	Proof of Concept
PPP	Public Private Partnership
QoS	Quality of Service
R&D	Research and Development
RAN	Radio Access Network
RAT	Radio Access Technology
RBW	Radio Bandwidth
RES	Resilience and Continuity
RF	Radio Frequency
RX	Receive
SC	Smart Cities
Si	Silicon
SOI	Silicon on Isolator
SW	Software
TDD	Time Division Duplex
TX	Transmit
UDR	User Data Rate
UE	User Equipment
UL	Up Link
V2X	Vehicle to Everything
vRAN	Virtualized Radio Access Network
WARP	Wireless Open-access Research Platform
WMP	Wireless MAC Processor
WP	Work Package

1. Introduction

The objective of this deliverable is to assess the achieved performance in the activities carried out in the other technical WPs (most notably WP6, the workpackage related to proof of concept (PoC) development) with respect to the Key Performance Indicator (KPI) targets outlined in [Fle11]. This performance analysis is mostly based on hands-on measurement of Flex5Gware PoCs, when available, or lacking these, results coming from simulation studies or analytical models derived mainly in work packages WP2, 3, 4, and 5. Next, this document compares these measurements and results with the requirements specified in [Fle11], outlining which have been met. Accordingly, this deliverable serves as a performance assessment summary of the Flex5Gware work.

This deliverable is organized as follows: Section 2 summarises the use cases considered in Flex5Gware and their corresponding KPIs. Section 3 reports the assessment of the achieved performance in terms of the target KPIs and expected results. Section 3 also contains an analysis of the level of KPI achievement in the context of the use cases. Finally, Section 4 concludes the document.

1.1 Reference material

Throughout this deliverable we will often make reference to use cases and PoCs defined in Flex5Gware [Fle11,Fle61,Fle62]. Although these will be summarised in the following sections, we provide a reference table with pointers to their detailed specifications below.

Table 1-1: Reference table

	Internal project references
Use cases	
Crowded venues (CV)	[S2.3.1, Fle11], [S3.3.1, Fle11],
Dynamic hotspots (DH)	[S2.3.2, Fle11], [S3.3.2, Fle11]
50+ Mbps everywhere (50+)	[S2.3.5, Fle11], [S3.3.5, Fle11]
Mobile broadband in vehicles (MBV)	[S2.3.6, Fle11], [S3.3.6, Fle11]
Smart cities (SC)	[S2.3.3, Fle11], [S3.3.3, Fle11]
Performance equipment (PE)	[S2.3.4, Fle11], [S3.3.4, Fle11]
V2X communication for enhanced driving (V2X)	[S2.3.6, Fle11], [S3.3.6, Fle11]
Proofs-of-concept	
1. On chip frequency generation	[S4.1.1, Fle11], [S3, Fle61, Fle62]
2. Active SIW antennas with integrated power amplifiers for the 20-40 GHz band	[S4.1.2, Fle11], [S4, Fle61, Fle62]

3. PAPR reduction and power amplifier pre-distortion	[S4.1.3, Fle11], [S5, Fle61, Fle62]
4. Multiband transmitter	[S4.1.4, Fle11], [S6, Fle61, Fle62]
5. Full duplex FBMC transceiver	[S4.1.5, Fle11], [S7, Fle61, Fle62]
6. High-speed low power LDPC decoder	[S4.1.6, Fle11], [S8, Fle61, Fle62]
7. HW/SW function split on SOC prototyping board for energy aware communications	[S4.1.7, Fle11], [S9, Fle61, Fle62]
8. Reconfigurable and programmable radio platform (terminal side) and SW programming performed and injected by the network	[S4.1.8, Fle11], [S10, Fle61, Fle62]
9. Flexible, scalable, and reconfigurable small cell platform	[S4.1.9, Fle11], [S11, Fle61, Fle62]
10. Flexible resource allocation in CRAN/vRAN platform	[S4.1.10, Fle11], [S12, Fle61, Fle62]
11. Multi-chain MIMO transmitter	[S4.1.11, Fle11], [S13, Fle61, Fle62]

2. Use Case Summary

2.1 Overview

As described in [Fle11], the project has selected three use-case families which together outline seven use cases. Together, these seven use cases assemble a wide span of requirements which serve as high-level targets for the implementation WPs (WP2, 3, 4, and 5) to address. In order to quantify the requirements in a structured way, a set of ten KPIs has been derived based on the fundamental 5G PPP KPIs described in [Euc13]. These KPIs capture all the performance aspects in the project, and are used for all use cases when outlining targets. In Table 2-1 the KPIs are listed, including the acronyms used in document.

Table 2-1: Flex5Gware KPIs

List of KPIs	Acronym
Flexibility, versatility, re-configurability	FVR
Cost	CST
Energy efficiency	NRG
Resilience and continuity	RES
Mobile data volume	MDV
Number of users	NoU
Bandwidth	BW
Latency	LAT
User data rate	UDR
Integration, size, footprint	ISF

In order to address the targeted KPIs, the project has developed eleven PoCs, which showcase results related to multiple use cases and KPIs. In Table 2-2, the connections among the PoCs, use cases, and KPIs are listed (for a description of the PoCs and the matching with the numbers displayed in Table 2-2, the reader is referred to [Fle62]. As seen, all uses cases will be addressed by at least two PoCs, and the spread is almost uniform. A small bias towards Dynamic hotspots and 50+ Mbps everywhere can be observed, but given the nature of these scenarios and their vital roles for 5G systems, this is physiological from Flex5Gware nature. Also, note that not all combinations of use cases and KPIs are addressed by the Flex5Gware PoCs. In these cases, results stemming from the technical work packages WP2, 3, 4, and 5 will be used to assess the fulfilment of the KPI targets (more details on this will be provided in Section 3). Also, it is worth highlighting that RES and LAT KPIs are almost not addressed by PoCs (this will be later analysed in Sections 3.2.4 and 3.2.8)

Table 2-2: Use cases, KPIs, and PoCs

Use Cases	KPIs	Connected PoCs
Crowded Venues	Flexibility, versatility, re-configurability	1,4
	Resilience and continuity	

	Mobile data volume	5,11
	Number of users	4,11
	Bandwidth	1,5
	Latency	
	User data rate	5,6,11
Dynamic Hotspots	Flexibility, versatility, re-configurability	1,4,5,7,8,9,10,11
	Energy Efficiency	1,6,7,8,9,10
	Resilience and continuity	
	Mobile data volume	4,5,11
	Number of users	4
	Bandwidth	1,4,5
	Latency	
	User data rate	5,6,7,10
50+ Mbps Everywhere	Flexibility, versatility, re-configurability	4,9,10
	Energy Efficiency	2,3.10
	Resilience and continuity	11
	Mobile data volume	4,9
	Bandwidth	2,4
	User data rate	10
Mobile Broadband in Vehicles	Flexibility, versatility, re-configurability	4, 7
	Mobile data volume	4
	Number of users	4
	User data rate	4,7
Smart Cities	Flexibility, versatility, re-configurability	8
	Cost	2
	Energy Efficiency	3,8
	Resilience and continuity	
	Number of users	2
	Latency	
	Integration, size, footprint	8
Performance Equipment	Cost	1,2
	Energy Efficiency	1,2,3
	Resilience and continuity	
	Number of users	2
	Bandwidth	1,2

	Latency	
	User data rate	2
	Integration, size, footprint	1,2
V2X Communications for Enhanced Driving	Resilience and continuity	8
	Latency	7,8
	User data rate	2

In the following section each use case is summarized at a high level, and targeted KPIs are described according to [Fle11]. Top-level requirements are also provided and further elaborated on the KPI performance summary in Section 3.

2.2 Targeted KPIs

2.2.1 Crowded Venues

In urban dense scenario, end users expect to have near-ubiquitous high-capacity seamless connectivity to wireless services. User density and demands are variable in time and space. Crowded venues represent an extreme case: there are some locations with massive crowds assembled for periods of time in small areas (e.g. for public or sport events, concerts, etc.). The kind of traffic is diversified: users can be interested in specific information during the event (scores, information about athletes or musicians, etc.). Users can watch HD videos, share live videos or post HD videos and photos on social networks. Accordingly, the sharing of HD videos and photos will be the main type of traffic, and it will constitute a heavier load.

For the crowded venues use case, the following KPIs were defined in [Fle11]:

- **Number of supported users (NoU):** In the above context, NoU represents the driving KPI, since a ultra-high NoU has to be handled. Even though the requirements for any other specific KPI, considered in isolation, may not appear to be overly stringent, they do become critical when dealing with a very large NoU.
- **User data rate (UDR):** The requirements were values already considered as LTE requirements (although the UL data rate is met only as a peak UL). Considering the foreseen NoU in a stadium, the requirements drive to a MDV with extreme peaks, which are challenging values that are not supported by LTE technologies.
- **Latency (LAT):** Real-time sharing of multimedia contents does not require a critical LAT. The requirement can be currently fulfilled in a 2-way RAN. However, with a large NoU, latency requirements become really challenging.
- **Resilience (RES):** the requirement is the standard value foreseen for 5G solutions. Considering the amount of traffic and the dynamic nature of the use case, it becomes a nonnegligible KPI: high RAT flexibility, depending on the type of traffic and the network load, is fundamental to ensure such level of reliability.
- **Flexibility, versatility, re-configurability (FVR):** for this use case, this KPI takes into account the time needed to timely switch on/off additional access points (needed when the events are taking place) or to reconfigure the network in case of failure (thus ensuring a uniform coverage and a high QoS). It plays a critical role when very large NoUs are considered.

In the table below, a summary of the requirements for each KPI is reported. Those values have been established in the early stage of the project (see [Fle11]) and used as key drivers for the use case.

Table 2-3: KPI details for the crowded-venues use case

Acronym	Requirement
FVR	Less than 30 s
RES	95 % (standard for 5G)
MDV (Peaks)	DL: 3.75 Tbps/km² (stadium:0.75Tbps) UL: 7.5 Tbps/km² (stadium: 1.5 Tbps)
NoU (Peak)	150000 users/km² (stadium: 30000 users/stadium)
BW (OBW)	3 GHz UL 1.5 GHz DL
LAT	10 ms [Elh15]
UDR	DL: 25 Mbps UL: 50 Mbps

2.2.2 Dynamic Hotspots

The Dynamic Hotspots use case concerns the data traffic offloading in dense urban scenarios where the network has to dynamically handle the presence of a high number of users' connections in a limited space (hotspot) and time. Because of that, an operator typically deploys a large number of network transmission points in an urban area, in order to support a peak-hour maximum number of connections. However, that maximum number of connections is reached only for a limited time in a day. Thus, the dynamic network reconfiguration of a Micro layer (i.e., a layer composed by a higher number of low-power transmission nodes) can be used to cover efficiently the hotspots placed in a urban area.
Typical locations for traffic hotspots are train/bus station, business center, schools, shopping malls, parks, squares or other popular places in a city. In a matter of minutes, the arrival of a train or the start of an event can greatly increase the traffic demand, and the latter can then revert to the original, lower baseline value just as fast.

In [Fle11] the KPI below are defined for the Dynamic Hotspot use case:

- **Flexibility, versatility, re-configurability (FVR).** This is one of main KPI, principally represented by the capability to handle the activation and deactivation of the layers that cover the hotspots, or a more generic transmission reconfiguration (such as e.g. the transmission bandwidth/power/mode or scheduling scheme/resources). The time needed to switch on/off a micro layer can be used to measure the capability to reconfigure the network in order to allocate the maximum capacity where the highest user traffic is generated.
- **User data rate (UDR)**. This KPI is used to evaluate the network performance in order to achieve a good quality of service for the served user. Each user has to perform 300 Mbps in DL and 50 Mbps in UL.
- **Mobile data volume (MDV).** The Dynamic Hotspot is a typical use case applicable in dense urban scenarios. Thus, the MDV takes into account the continuous increase of mobile data traffic over the next years. The values for this KPI are shown in the table below.
- **Bandwidth (BW).** This KPI is important especially for the micro layer used to boost data traffic. Larger channelization bandwidth will be supported in order to increase the efficiency of micro layer transmission. The increase of the channelization bandwidth leads to the simultaneous increase of the frequency band used for the transmission. Many challenges are linked to the transmissions on higher band, in particular higher device cost and energy consumption.
- **Energy efficiency (NRG).** This KPI represents how energy can be saved by exploiting flexible network reconfiguration and more efficient transmission techniques for signals at higher frequency (from 2GHz to 60GHz).

Table 2-4: KPI details for Dynamic Hotspot

Acronym	Requirement	Comments and gap to currently available
FVR	< 5 minutes	Time requested to adapt the system to a change of network configuration (switch on/off of one or more cells)
NRG	from 40 % to 60 %	The most relevant way to reduce the power consumption is to improve the way energy is spent, exploiting the network re-configuration. This KPI is measured by assessing the energy consumption of a *dynamic* Micro layer over an always-on one.
MDV	Traffic Density DL: 750 Gbps/km² UL: 125 Gbps/km²	KPI for 5G network [Elh15] is to increase especially average and cell-edge capacity in comparison to LTE Rel-12 performance.
BW	from 100 MHz to 1 GHz (OBW)	Both the network and the users have to exploit a larger available transmitting band. From traditional 4G operational bandwidth (OBW) to mmWave OBW should be supported in a Dynamic Hotspot scenario
UDR	DL: 300 Mbps UL: 50 Mbps	These values of user experience data rate have to guarantee also at the cell edge [Elh15].

2.2.3 50+ Mbps Everywhere

In the 50+ Mbps Everywhere use case, users (mostly human) require high minimum sustained data rates independently of time and location. In this use case, such reliable communication is also driven along with low energy consumption. The main reason for this is that areas with sparse network infrastructure (larger cells) will incur in higher propagation losses and, consequently, meeting the 50+ Mbps requirement could imply higher transmission power unless energy saving strategies are applied.

In this setting, the following KPIs were defined in [Fle11] for the 50+ Mbps everywhere use case:

- **User data rate (UDR)**. This KPI must be guaranteed at every location of the service area, even at the cell edge in remote rural areas. In particular, each user should be able to experience a data rate of at least 50 Mbps in downlink and 25 Mbps in the uplink.
- **Mobile data volume (MDV).** Based on the minimum throughput requirement of 50 Mbps together with the active user density in different areas, the mobile data volume can be computed as:
    1. Far remote rural: 500 Mbps/km^2.
    2. Rural: 5 Gbps/km^2.
    3. Suburban: 25 Gbps/km^2.
- **Bandwidth (BW).** Taking a conservative estimate, a safe minimum value of the spectral efficiency that will be achieved everywhere in the cell under all circumstances is $\boldsymbol{\varepsilon} = \mathbf{1}$, which implies that the minimum maximum bandwidth that will need to be supported by terminal devices is $\boldsymbol{BW} = \mathbf{50}$ MHz. The main implication of

the above result is that terminal devices should be capable to operate at bandwidths of 50 MHz or above.

- **Flexibility, versatility, re-configurability (FVR).** For the 50+ Mbps everywhere use case, flexibility and versatility will be mainly provided at the base station by, e.g., multiband transmit-chains that provide a high degree of versatility with regard to the implementation for different power levels, number of antennas and supported radio bands. In this context, re-configurability should also be based on different context estimates to modify the operation of the RAT in a timely manner, to adapt it to context variations and sudden changes in the scenario to maintain the user rate above the threshold.
- **Resilience, continuity (RES).** A significant level of reliability and continuity is required in order to ensure that the 50+ Mbps are guaranteed even in the case where the user is on the move or in the presence of rapidly changing channel conditions. The selection of MIMO technology is of paramount importance in this use case as the use of multiple antennas can provide an efficient method to increase the signal resilience without increasing the transmission power.
- **Energy efficiency (NRG).** Since the requirement of 50+ Mbps has to be met everywhere and at the cell edge in particular, this might require additional transmission power. Thus energy saving strategies both at HW and SW domains will be required that represent a reduction of 25 – 60 % with respect to current existing solutions.

Table 2-5: KPI details for 50+ Mbps everywhere use case.

Acronym	Requirement
FVR	Capability to provide multiband operation (e.g., 6x20 MHz channels)
NRG	Energy savings in the range of 25 - 60 % with respect to current existing solutions
RES	Resilience is achieved via MIMO operation, with a minimum number of 8 transmitters at the base station.
MDV	Far remote rural: 500 Mbps/km^2. Rural: 5 Gbps/km^2. Suburban:25 Gbps/km^2.
BW	≥ 50 MHz
UDR	DL: 50 Mbps (100 Mbps, if possible) UL: 25 Mbps

2.2.4 Connected Vehicles – Mobile broadband in vehicles

Concerning the “mobile broadband” traffic, namely, mobile devices inside vehicles, the requirements are very much related to the other use cases dealing with broadband. However, conditions are made more challenging due to vehicle plating and speed, and the means of traffic provisioning due to the specifics of a highly mobile scenario, with highly varying density. The following KPIs were defined for this type of communications:

- **Flexibility, Versatility, and Re-configurability (FVR)**. The vehicular scenario imposes rapidly-changing conditions due to various reasons, e.g., high speeds in highway scenarios and fast fading in urban scenarios. Because of this high dynamicity, it is critical for the card to be able to change its mode of operation, and this change must be quick enough.
- **Mobile data volume (MDV)**. During traffic jams or heavily congested rush hours, vehicles could be travelling at very low speed, causing peaks in mobile data volume. Using heterogeneous RATs with point of attachments placed in well-defined locations (i.e., intersections, traffic light posts) better connectivity (in terms of both volumes and number of users) may be achieved. Capacity may be provided just where and when needed, selectively offloading flows from the cellular network to the small-cell infrastructure, and taking advantage of other communication means available (i.e., 802.11 AP inside the vehicle).
- **User data rate (UDR).** Users within vehicles are more tolerant to reduced data rates, which eases the requirements, in particular considering that the car introduces 15-20 dB of additional attenuation**.**
- **Number of users (NoU)**. In addition to traffic volume, the number of devices simultaneously connected is potentially very high, again due to traffic jams or heavily congested rush hours, being comparable to mass people gatherings. As in these cases, mobility patterns are predictable and, furthermore, mobility is constrained by the road infrastructure, which should enable the design of appropriate schemes to provide the required capacity.

Table 2-6: KPI details for the Connected Vehicles – Mobile Broadband in Vehicles use case

Acronym	Requirement
FVR	Ability to change the operation parameters of the RAT, or to switch between RATs.
MDV	Urban: 150 Gbps/km^2. Suburban: 50 Gbps/km^2. Highway: 25 Gbps/km^2.
UDR	Instantaneous: 50 Mbps/vehicle (DL) Operation: 5 Mbps/vehicle (DL)
NoU	Urban: 1000-3000 vehicles/km^2 Suburban: 500-1000 vehicles/km^2 Highway: 100-500 vehicles/km^2

2.2.5 Smart Cities

Within the Flex5Gware perspective, a significant part of the focus is on 5G network enhancements related to the Smart Cities use case. Accordingly, most of the proposed KPIs have a network-oriented perspective. These network KPIs measure the quality of the communication medium through which observed data are transferred from the measuring/acting devices to the data processing or managing servers. In addition to the network-oriented perspective, Flex5Gware also addresses enhancements on 5G terminal devices. For that reason, in some KPIs, such as the one related to energy efficiency, the focus is shifted towards the IoT device. Before presenting the KPIs related to this use case, it is important to highlight that the effort presented in this section is also being considered in the standardization bodies, such as ITU, where a specific working group has been created to cover IoT-related requirements.

The KPIs related to the Smart Cities use case are:

- **Energy efficiency (NRG)** is an important target for Smart Cities especially in terms of IoT device power consumption. At the device side, the idea is to prolong the device lifetime and delay maintenance operations as much as possible.
- **Number of supported users (NoU)** is also instrumental to this use case.The number of IoT devices in use is expected to grow exponentially in the near future. Thus, the network is supposed to be able to handle this rising number of IoT devices together with human users inside the cities.
- **Integration size (ISF)** of IoT devices is quite important as well. Devices are supposed to be smaller and smaller while their computational capabilities grow and their energy consumption is reduced. A trade-off among all these requirements must be achieved so as to guarantee viable IoT devices.
- **Cost (CST)** is also an inherent KPI when talking about IoT devices. They are supposed to be cheap and powerful, but the main cost achievement can be obtained from the OPEX perspective, enabling network operators to reduce the cost of deployment and re-configuration of IoT nodes obtaining higher RoI figures.
- **Resilience (RES)** is a hot topic in the R&D world when talking about smart cities [Cit14]. Nodes should be able to recover from power or communication shortages without losing their data. This must also occur jointly with the size and cost reduction.
- In terms of **flexibility/versatility/re-configurability (FVR)**, on this Smart city use case Flex5Gware aims at reducing the time needed to reconfigure the radio connectivity based on the information gathered by IoT devices. The reconfigurability needs of 5G-driven smart cities are also considered.
- Finally, **latency (LAT)** can be important to certain applications. While smart metering or environmental monitoring do not have strict latency requirements, some other applications for smart cities, such as user detection, need immediate reaction, and, thus, latency must be considered.

Table 2-7: KPI details for Smart Cities use case.

Acronym	Requirement
FVR	Less than 30 s radio reconfiguration time
CST	Reduction factor: 1.5x reduction.
NGR	At least two years for IoT devices just sending data up to 10 times a day. At least one year on more communication intensive cases.
RES	Power and communication backup modes.
NoU	1.000 IoT devices per km^2 in cities in addition to regular users.
LAT	Time unit. Up to 1 min on low-priority IoT applications (such as environmental monitoring) and less than 5 s on high-priority ones (i.e. people detection)
ISF	Reduction factor: 1.5x reduction.

2.2.6 Performance Equipment

Although it is foreseeable that the vast majority of connected devices in the global 5G system will be simple sensors and actuators, still a lot of high-performance equipment will be connected to the network and call for high-performance services. However, it is important to realize that these devices will not, despite the high-performance characteristics, necessarily be tailored in hardware for a specific purpose, but will instead to a large extent rely on high-volume general-purpose transceivers and computational platforms, with dedicated software to create specific feature sets. This means that the implementation will still face significant constraints on cost, size, power consumption etc.

The following KPIs were defined in [Fle11] for this use case:

- **User data rate (UDR)**. 5G terminals shall support aggregation of data flows from different technologies and carriers, including handling of multiple bands simultaneously. Especially global roaming capabilities without degrading performance are expected, as well as support for multiple modes of operation (TDD/FDD, full/half duplex). Support for all deployed connectivity standards will also be regarded as mandatory, and expected user equipment data rates are between 50 Mbps up to 10 Gbps and beyond depending on deployment and use case.
- **Operational bandwidth (BW)**. The 3GPP standardization work for 5G has just started, which means that user equipment operational bandwidth is not set yet. However, as a first assumption, +100 MHz can be assumed for performance devices supporting the highest throughput levels.
- **Latency (LAT)**. Performance equipment should support hybrid scenarios which combine low latency and high data rates. As described by ITU [Fet14] the required end-to-end latency may be as low as 1 ms in specific 5G use cases. This total latency must be shared among the acting blocks in the transmission and data processing. The total time for device processing could be as low as 300 µs for receiving and transmitting, respectively.
- **Energy efficiency (NGR)**. As part of a continuous evolution, 5G devices are expected to show significant longer battery life compared to 4G counterparts. This goes across all product segments, including performance equipment where one example highlighted by the NGMN is at least three days normal operation of a smartphone.
- **Cost (CST)**. The trend which has been observed for many years during 4G is expected to continue, i.e. declining sales price for consumer equipment. Given this, 5G devices must be as cost efficient as the previous generation to have a good market penetration. Although added value in terms of technical performance and GUI experience may balance the situation, especially for performance equipment, the HW cost and manufacturing cost must be on par with, or cheaper than similar products today.
- **Number of user (NoU)**. It is a valid assumption that high-end 5G devices, e.g. smartphones, tablets, laptops etc., will capture a significant part of all sold user equipment. Given the lifespan of 5G this will equate to tenths of billions of sold devices worldwide.
- **Integration, size, footprint (ISF)**. Determined by physical parameters set by human interaction and aesthetics, high-grade 5G devices must show at least comparable physical footprint as available on the market today.
- **Resilience and continuity (RES).** Future applications will determine the requirements for resilient operations, and the spread will be large. For critical applications in industrial and healthcare segments the demands on downtime could potentially be very high.

Table 2-8 KPI details for the Performance Equipment use case.

Acronym	Requirement
CST	The same physical footprint and bill of material (BOM) compared to 4G high performance devices today.
NRG	A smart phone should handle more than three days on battery in normal use. For less performing devices multiple days are expected (more than 10

	days for sensors etc)
RES	99.999% availability for the most critical use cases
NoU	Billions of users
BW	100 MHz operational bandwidth
LAT	150 µs from antenna to processed data
UDR	10 Gbps in specific scenarios, 100 Mbps in urban areas, 50 Mbps everywhere
ISF	Same physical footprint and BOM cost compared to 4G high performance devices today.

2.2.7 Connected Vehicles – V2X communication for enhanced driving

With "machine initiated" traffic, the objective is to support driving or enable automatic driving, which introduces a different set of requirements. This traffic includes three different types of applications: Vehicle-to-Vehicle (for collision avoidance, autonomous driving, vehicle platooning), Vehicle-to-Pedestrian (collision avoidance), and Vehicle-to-Infrastructure (for fast dissemination of emergency information). For this type of communication, the relevant KPIs include:

- **Resiliency (RES).** One key objective is to maximise the delivery ratio in this type of communications. To this aim, there are choices such as enhanced multicast techniques, use of multiple technologies in parallel, including multi-hop short range communications or broadcast with reliable coding schemes.
- **Latency (LAT)**. There are two paradigms in this type of communication: for assisted driving, namely, see through or other enhanced vision app, the requirement is in accordance with human responses to video, which is in the order of tens of milliseconds. For automated operations, delay guarantees are more restrictive, due to its different nature and the lack of human interaction.
- **User data rate (UDR).** See-through applications or bird's eye view applications, while not requiring stringent constrains in terms of delay, do require a relatively high bandwidth as they involve the transmission of video. In contrast, automatic driving application do not impose mayor constraints in terms of UDR.

Table 2-9: KPI details for the Connected Vehicles - V2X Comm. for Enhanced Driving use case

Acronym	Requirement
RES	10^{-5} loss rate for automated operation (overtake, collision avoidance) 10^{-3} for status updates on trajectory (crossings)
LAT	10 ms for automated operation, 50 ms for streaming (see-through, bird's eye view in intersections)
UDR	10 Mbps for see-through, 40 Mbps for intersections.

3. Evaluation of Flex5Gware Results

3.1 Flex5Gware approach

As described in the Flex5Gware DoW, the overall objective of Flex5Gware has been to provide the building blocks that facilitate the delivery of highly reconfigurable HW platforms together with HW-agnostic SW platforms taking into account increased capacity, reduced energy footprint, as well as scalability and modularity, to enable a smooth transition from 4G mobile wireless systems to 5G. In particular, this overall objective has been implemented by pinpointing specific implementation challenges of 5G HW and SW platforms, targeting building blocks of both network elements and devices. This implementation complexity analysis has been used, for example, to indicate the viability of anticipated solutions for 5G in the form of eleven PoCs (see [Fle62]).

According to this bottom-up approach, where the basis of the analysis is composed of eleven PoCs of different aspects of 5G platforms, the overall Flex5Gware performance is mainly evaluated via measurements taken on these PoCs (which can themselves be regarded as the integration of building blocks). This is especially true of KPIs that are inherently more low-level, such as FVR, NRG, BW, or ISF. However, for the sake of completeness, in the analysis that we provided in [Fle11] we also took into account KPIs that are more related to system-level metrics (like MDV, NoU, LAT, or RES) and for which 5G HW and SW platforms will have to fulfill certain requirements, but that are not directly measurable with SotA platforms, because end-to-end 5G platforms are not available yet. In this second case, approximate quantitative results (such as orders of magnitude) can sometimes be provided based on a very simple system-wide model analysis. In some other cases, only qualitative improvements can be provided. For the system-wide model analysis, a set of deployment scenarios have been considered in the project (DS1, DS2, DS3, and DS4). Details on these deployments can be found in [Fle22] and are ommitted here. Finally, details on the system-wide model used to derive numerical values for some KPIs can be found in Annex A (Section 5).

In the light of the above statements, three different categories of outcomes related to KPIs have been defined:

- Category A: These are quantitative results for KPIs that can be directly measured from measurements from the PoCs (or directly evaluated from measurements)
- Category B: These are quantitative results for KPIs that are evaluated based on a simple system-wide model, which takes as inputs some parameters that can be directly extracted from the PoCs.
- Category C: These are qualitative results that provide some progress towards a given KPI, but whose impact cannot be evaluated numerically.

In the following subsections, the level of compliance with the targets for all Flex5Gware KPIs is presented. Each subsection includes a table that relates the different KPI targets for each use case with the results from the Flex5Gware project. As pointed out before, due to the experimental nature of the Flex5Gware project activities, the core of the contribution to KPIs is taken, whenever possible, from PoCs (integrated in WP6) rather than contributions from the single building blocks (which are developed within WP2, 3, 4, and 5). However, since not all KPIs are fully addressed by PoCs only, in some cases, contributions from the technical WPs (WP2, 3, 4, and 5) are also included here. Finally, each subsection also presents a table that summarizes the contributions that PoCs have made towards a given KPI.

3.2 Performance evaluation with respect to target KPIs

3.2.1 FVR: Flexibility, Versatility, Re-configurability

Being one of the most prominent project KPIs, FVR relates to system capabilities associated with flexibility and network adaptation to suddenly changing conditions. In total, eight out of eleven PoCs address this KPI, which testifies its importance. One key implementation aspect, besides the actual reconfiguration, is time overhead, which is a target for all involved PoCs. This addresses both start-up times to boot a specific platform, e.g. to enable a new network node or band configuration, and the time it takes to find the optimal configuration settings for a given scenario that is exposed to transient effects, e.g. a change in RAT co-existence or the bring-up of an algorithm to boost existing RAT performance.

In PoC 1 and 4, analog radio properties related to start-up times have been looked into and verified to be complient with project targets for both Crowded Venues and Dynamic Hotspots. This is also true for the algorithm settling time target in PoC 4 related to band flexibility.

PoC 5 addressed full-duplex as a network operation mode, and has been verifying that the coefficient correction time needed, based on sample iteration, is far less than the total network reconfiguration time target for both Dynamic Hotspots (5 mintes) and Crowded Venues (30 seconds). The situation is similar in PoC 7 where the HW-SW split can be reconfigured in just a few seconds.

In PoC 8 the network configuration is looked into as a mean to reach optimal performance based on local SW agents and cognitive radios interacting with a remote network controller. The time needed is verified to be 10% of the outlined KPI target for Dynamic Hotspots, and spot on the target for Smart cities.

PoC 9 and PoC 10 targeted to bring up and plan network functionality in the software domain. PoC 9 addressed a flexible, scalable small cell platform able to allow third parties to deploy SDR processing functions based on raw samples or higher-layer traffic. The required configuration time was measured to be just a few seconds and, thus, way less than the overall target of 5 minutes. In PoC 10 the scope has been to analyse the effects of resource allocation algorithms for CRAN/vRAN networks and lab results indicate a configuration time below one minute, which also shows good margin to the Dynamic Hotspots KPI target.

Finally, PoC 11 has demonstrated 8 implemented transceiver chains to be configured in less than 1 second, which is complient with the Dynamic Hotspots KPI on 5-minute network reconfigurability.

Table 3-1: Table of Use Cases for FVR KPI

Use case	High level FVR requirements	Addressed technology components	PoC/WP	Achieved results
Crowded venues	Less than 30 seconds to switch on-off additional access points or to reconfigure the network	Start up and settling time for the PLL	1 / -	The start-up time is too short to be measured and will not limit the use case requirement. The maximum settling time is below 2us.
		Flexible radio band support	4 / -	The frequency agility of multiband transmitters is demonstrated in lab. The applied concepts allow to reconfigure the transceiver within a few seconds.
		Switching between MIMO/Full duplex	5 / -	Between 200-1000 samples needed to adjust coefficients. This corresponds to less than 20 us.
Dynamic hotspots	Less than 5 minutes to adapt the over-all system to a change of network configuration	Start up and settling time for the PLL	1 / -	The start-up time is too short to be measured and will not limit the use case requirement. The maximum settling time is below 2us.
		Multiband operation	4 / -	The multiband support has been verified in lab. The configuration time is estimated to be less than 30 seconds.
		Full duplex startup-time	5 / -	Between 200-1000 samples needed to adjust coefficients. This corresponds to less than 20us.
		Flexible network HW-SW configuration	7 / -	Changing the WCP of interest in RFIC, baseband processor, and the LENA system takes less than 2s.
		Dynamic network configuration	8 / -	Measured average reconfigurations time is about 30s going from bad performance to an optimal solution.

		Ability to deploy a new eNodeB	9 / -	The bring-up of the Linux based virtual machine is below 5s, including the application layer.
		Reallocation of network resources	10 / -	Lab measurements on computers running the implemented SW show a configuration time of < 50s and a switch off time < 5s.
		MIMO transceiver reconfiguration	11 / -	A number of 8 chains are successful implemented in a single digital component (FPGA) and verified in lab. The observed reconfiguration time is < 1s.
Smart cities	Less than 30 seconds to reconfigure the radio connectivity based on the info gathered by IoT devices.	Automatic reconfiguration of the radio platform	8 / -	Measured average reconfigurations time is about 30s going from bad performance to an optimal solution.
50+ everywhere	The capability to provide multiband operation	Multiband operation	4 / -	The support of 3 bands has been verified in lab.
		Reallocation of network resources	10 / -	The ability to power up and down cells has been studied and shown in lab environment together with the corresponding reallocation of network resources in the different bands.
Mobile BB in vehicles	The ability to change RAT operation parameters, or to switch between RATs	Multiband operation	4 / -	The frequency agility of multiband transmitters is demonstrated in lab.

Next, in the table below we detail the PoCs in which the FVR KPI has been assessed.

Table 3-2: Table of PoCs that address the FVR KPI

PoCs	FVR content targets	Achieved results
1	PLL start-up time and frequency reconfiguration time in the range of milliseconds.	This parameter was not measured in the lab since it is too short to be accurately measured. Simulations indicate < 20 us.
4	TX re-configuration time < 1 s for 1-6 carriers and their position in 1-3 radio bands. The algorithm settling time should be < 30s.	The number of radio bands has been verified in hardware, whereas the re-configuration time is a theoretical estimate indicating < 1s. The algorithm settling time is expected to be < 30s.
5	Full-duplex algorithm implemented in real hardware	The system is fully integrated in hardware and tested in lab.
7	Reconfiguration time, granularity of WCPs, and HW-SW partitioning	In lab verified ability to reconfigure specific HWA and SW processing blocks of the LTE communication stack, as well as modification of specific WCPs.
8	Context-aware decision making and advanced network function virtualization, in order to increase the number of the available physical resources	Lab verification shows concurrent LTE-U and WiFi transmissions according to project targets.
9	Time that it takes to instantiate a virtualized SDR function (which is both time to deploy and time to reconfigure).	Instantiation time less than 5 s
10	Configuration time to switch on a node and for switching it off	Lab measurements on computers running the implemented SW show a configuration time of < 50s and a switch off time < 5s.
11	Signal generation of the “Compact multi-chain transmitter” designed for generating multiple RF signals	A number of 8 chains are successful implemented in a single digital component (FPGA) and verified in lab. The observed reconfiguration time is < 1s.

As seen in the above tables, all PoCs achieve results which are in line with, or better than the KPI targets originally stated for the addressed use cases. For all PoCs the maturity level is according to the expectations and project plans, which means actual hardware and lab verification where applicable. This, in combination with a large footprint (eight out of eleven project PoCs being represented), can only be viewed as a very successful KPI and a strong outcome from the project. This was also anticipated as FVR is a key component of the Flex5Gware story.

3.2.2 CST: Cost

The CST KPI is, in the first place, highly connected to integration levels and physical properties, thus similar to the ISF KPI (Section 3.2.10), but in addition factors in technology and deployment costs. Three PoCs have addressed the CST KPI by using high-volume standard technologies for implementations. This applies especially to PoC1 and PoC 2 where the actual technology realization is low-cost with high-volume integration. For PoC 6 the LDPC decoder design has been synthesized, including place & route, to compare the implementation cost to published SotA by using the metric UDR (user data rate) per mm^2.

Table 3-3: Table of Use Cases for CST KPI

Use case	High level CST requirements	Addressed technology components	PoC/WP	Achieved results
Smart cities	1.5 times cost reduction	Co-integration of CMOS PA and antenna	2 / -	This is a category C KPI as the cost reduction for Smart Cities is only based on assumptions. However, the cost saving per device thanks to standard PCB manufacturing technology (simple antenna stack) and high integration CMOS PA will be significant for high volume numbers.
Performance equipment	A cost efficient high volume technology implementation using maximum integration	Low cost, high volume CMOS technology	1 / -	The 20 GHz PLL implementations in CMOS SOI technology shows wanted performance in lab.
		Co-integration of CMOS PA and antenna	2 / -	Two SIW antennas has been co-integrated with two different PAs and measured in lab (28GHz and 19GHz). One of the PAs (28GHz) is fabricated in a high volume CMOS technology.
		New LDPC architecture requires less Si area	6 / -	Given the metric UDR per mm^2 silicon, the proposed implementation outperforms reported SotA.

Next, in the table below we detail the PoCs in which CST KPI has been assessed.

Table 3-4: Table of PoCs that address CST KPI

PoCs	CST content targets	Achieved results
1	Same BOM cost as for 4G systems (but using new 5G frequency bands)	Evaluated based on architecture and CMOS implementation. Verified in lab.
2	Co-integration of CMOS PA and antenna to reduce footprint and cost. Low cost CMOS PA at 28 GHz.	The co-integration is achieved and lab measurements show results in line with expectations.
6	To provide an architecture which minimizes silicon area for a given throughput.	The new LDPC architecture requires less silicon (Si) area (0.9 mm^2) compared to SotA

The Category-A project results targeting CST have all been demonstrated, either based on assembled and measured SotA hardware implementations (PoC 1 and 2), or calculated to allow for SotA benchmarking (PoC 6). The results clearly show how Flex5Gware has addressed and pushed the 5G implementation cost in the right direction. The relatively low level of active PoCs (only three out of eleven) is a result of the project scope, which primarily targets network performance and flexibility.

The Category-C target in PoC2 is not only related to the obvious savings made by the increased integration level and highly cost-efficient building practice. Also the gained power efficiency will contribute to a lower operating cost, which - combined with very high deployment numbers - will account for a significant cost benefit. Nonetheless, such gains are obviously rather difficult to quantify.

3.2.3 NRG: Energy

The NRG KPI is related to the expected energy consumption reduction in 5G networks when compared to 4G. This KPI has two different aspects to it. On one hand, when referred to network equipments, it is expressed in terms of a percentage that represents the target energy consumption reduction. On the other hand, when referred to user equipment, it is usually expressed in terms of battery lifetime. Together with the FVR KPI described above in Section 3.2.1, the NRG KPI is one of the project KPIs for which Flex5Gware has provided more results. In particular, eight out of eleven PoCs address this KPI.

Table 3-5: Table of Use Cases for NRG KPI

Use case	High level NRG requirements	Addressed technology components	PoC/WP	Achieved result
Dynamic hotspots	40-60 % overall energy saving	Power efficient decoders	6 / -	Energy efficiency of 61 pJ/bit, which contributes to the overall energy savings.
		Flexible network HW-SW configuration	7 / -	Energy savings of up to 60 % can be achieved.

		Dynamic network configuration	8 / -	7.2 % of energy consumption reduction.
		Multitenancy in a single processor	9 / -	Savings between 50 and 75 %.
		Switching on/off small cells	10 / -	Overall network energy savings between 16 and 66 %.
Smart cities	At least 2 years battery lifetime for IoT devices sending data up to 10 times a day. Up to 1 year lifetime in more restrictive cases.	Antenna + PA design with high energy efficiency	2 / -	Energy efficiency increase of 31 %, which contributes to reduction of battery consumption.
		PAPR reduction techniques	3 / -	Energy efficiency increase of 6 %, which contributes to reduction of battery consumption.
		Low power transmission mode for sensing devices	8 / 5	Achievement of an expected battery lifetime of 2 years.
Perf. equipment	More than 3 days on battery in normal use. For less performing devices multiple days are expected (more than 10 days for sensors etc.).	High frequency band operation	1 / -	More than 20 % energy consumption reduction with respect to SotA, which contributes to overall battery lifetime.
		Antenna + PA design with high energy efficiency	2 / -	Energy efficiency increase of 31 %, which contributes to reduction of battery consumption.
		PAPR reduction techniques	3 / -	Energy efficiency increase of 6 %, which contributes to reduction of battery consumption.
50+ everywhere	Total network energy savings in the range of 25 - 60 % with respect to current existing solutions.	Antenna + PA design with high energy efficiency	2 / -	Energy efficiency improvement of 31 %, which contributes to overall energy savings.
		PAPR reduction techniques	3 / -	Energy efficiency increase of 6 %, which contributes to overall energy savings.
		Switching on/off small cells	10 / -	Overall network energy savings between 16 and 66 % and guarantees of link quality to cell edge users.

Next, in the table below we detail the PoCs in which NRG KPI has been assessed.

Table 3-6: Table of PoCs that address NRG KPI

PoCs	NRG content targets	Achieved result
1	PLL FOM in line with SotA and not limiting the system NRG targets. The frequency synthesizer must have low energy consumption to enable integration of many transceiver chains in a massive MIMO implementation.	18 mW of power consumption per PLL, which is around > 20 % reduction compared to SotA for similar center frequencies at 28 GHz
2	Energy efficiency of the integrated antenna + PA	Achieved energy efficiency of 31 % improvement
3	Combining WSLM and DPD to achieve a SotA PAPR reduction technique	0.5 dB of PAPR reduction, which translates into an increase of energy efficiency for the PA of about 6 % [Wul05]
6	Energy consumption optimized decoder architecture based on compression techniques	Measured energy per bit of the proposed solutions between 62 and 233 pJ.
7	Network energy consumption to be measured for different HW and SW distributions	Most of the power consumption takes places at RFIC and BB processing. Depending on the chosen configurations, energy savings of up to 60 % can be achieved.
8	Reconfiguration mechanisms providing network function virtualization (SW execution). Computational operations handled in a single low-power microcontroller	7.2 % energy reduction when moving functions from HW to SW with energy efficiency criteria.
9	Showcase energy increase as the number of tenants in a small cell increases is below the addition of individual energy consumptions	4x number of tenants in 5 MHz bandwidth and 2x number of tenants in 10 MHz, which corresponds to a similar factor in energy consumption savings
10	Network algorithm to support on/off cell switching capabilities	Energy savings between 16 and 66 % thanks to on/off cell switching

Similarly as with the FVR case, all PoCs achieve results which show excellent progress towards the achievement of the Flex5Gware NRG KPIs for all use cases for which energy was considered relevant. In addition to this, the NRG KPI has a strong presence both in terms of use cases that address it (four out of seven) and, also, in terms of PoCs that provide NRG-related measurements and results (eight out of eleven project PoCs being present). Thus, the NRG KPI is, together with FVR, one of the strongest outcomes from the project.

3.2.4 RES: Resilience

The resilience and continuity KPI refers to the probability that a certain amount of data is successfully delivered to its destination within a given time frame. This KPI is especially relevant in wireless environments due to, e.g., the rapidly changing nature of the propagation conditions. Within the Flex5Gware project, this KPI can be mapped one-to-one to the 5G-PPP KPI P4, *"Creating a secure, reliable and dependable Internet with a "zero perceived" downtime for services provision*".

Flex5Gware aims to improve reliability of Internet connectivity by addressing resilience and continuity through two main contributions:

1) The SW platforms developed in Flex5Gware will be capable of selecting the most appropriate RAT among the plethora of possibilities offered by 5G, depending on the particular scenario and propagation conditions, in such a way that the service resilience and continuity is guaranteed (i.e., by allowing to choose a RAT which is less performing in terms of rate, but whose resilience is higher, or by choosing to use the massive MIMO capabilities to improve the link quality instead of improving the user rate).

2) Thanks to the multi-node coordination layer that will be developed within Flex5Gware, the reliability will be improved from a network-wide perspective rather than from the point of view of a single link.

In Table 3-7 a list of technology components is associated to each use case. The technology components shown therein are the most promising to improve the Resiliency (RES) in a radio access network.

Table 3-7: Table of Use Cases for RES KPI

Use case	High level RES requirements	Addressed technology components	PoC/WP	Achieved result
Crowded venues	The requirement is the standard value foreseen for 5G solutions, 95%. High RAT flexibility is fundamental.	CPS-based capacity estimator	- / 5	Combining CPS analysis with proportional fairness optimization, it is possible to drive a cellular network that capitalizes on D2D communications to increase the resilience when the cellular link quality is low.
Smart Cities	Power and communication backup modes. Nodes should be able to recover from power or communication shortages without losing their data.	API for dynamic radio-frequency bandwidth	- / 5	This API acts as an enabler, adapting the resulting devices to other partners' needs in their envisioned tests.

Perf. equipment	99.999% availability for the most critical use cases. For critical applications in industrial and healthcare segments the demands on downtime could potentially be very high.	No technology addressed this UC/KPI combination	- / -	No results are available.
50+ everywhere	Resilience is achieved via MIMO operation, with a minimum number of 8 transmitters at the base station. Increase the signal resilience without increasing the transmission power.	Increase the achievable spectral efficiency by means of MIMO operation. (Category C)	11 / -	The PoC has eight parallel streams and it can be cascaded so that the number of antennas can increase significantly. MIMO operation increases resilience thanks to the diversity aspect it provides.
Vehicle2X	10^{-5} loss rate for automated operation (overtake, collision avoidance) 10^{-3} for status updates on trajectory (crossings)	API for dynamic radio-frequency bandwidth, (Category C)	8 / -	Dynamic bandwidth adaptataion can increase the system resilience.

Next, in the table below we detail the PoCs in which RES KPI has been assessed.

Table 3-8: Table of PoCs that address RES KPI

PoCs	RES content targets	Achieved result
2	Large antenna BW to account for detuning, to enable V2V and V2X in addition to other schemes.	Modulated signal measurements performed on CMOS PA verified in lab with adequate quality. However, no specific RES results are obtained.
8	Ability to anticipate the poor performance of a given RAT, thanks to advanced monitoring capabilities, so a smooth handoff can be performed (including the bi or multi-casting of information through different paths) without losses, increasing resilience. Ability to autonomously recover from power/communication failures.	Dynamic bandwidth adaptation: implemented in WARP boards and based on the 802.11 standard. TX is able to adapt dynamically transmission BW (i.e. 5, 10 or 20 MHz) and RX can adapt reception by preamble detection. These adaptations can be used to increase resilience.

11	Multi-antenna operation to increase the resilience thanks to the added diversity	The PoC has eight parallel streams and it can be cascaded so that the number of antennas can increase significantly.

Based on the results shown in this section, we can summarize that the improvement of RES is addressed to some extent in the different PoCs, but it is difficult to evaluate the overall gain.

3.2.5 MDV: Mobile Data Volume

This KPI represents the amount of both uplink and downlink data that a network is capable to support in a geographical area. The value is computed as an aggregated data rate divided by a given area. Similar to what is described in [Fle11], this value depends on the use cases: places with a high population density or crowded-venue scenarios have to support huge amounts of traffic from and toward final users. Remote or rural areas anyway have to guarantee the capability to support a good amount of data traffic. The reference values for MDV are reported in Table 3-9 on the basis of the use-case scenarios where this KPI is more relevant.

In the table below a list of technology components is associated to each use case.The technology components shown therein are the most promising to improve MDV. The multi-band operation is described in PoC 4 [Fle62]: this technology component exploits broadband and multiband capabilities of components to realize transceiver chains, which support concurrent operation in multiple radio bands. This allows one to reduce the hardware complexity by decreasing the number of implemented transceivers in order to support multi operational bands. The increase of operational bandwidth is a key component to support the 5G MDV in the majority of the use cases.

Full-duplex operation is shown in PoC 5 [Fle62]: this technology component allows an increase of capacity of the cell, since one resource block is used at the same time for uplink and downlink. The virtualized process at the edge, described in PoC 9 [Fle62] is a technology component that allows the support of multiple virtual base band on the same hardware, thus maintaining the same infrastructure while enabling an increase in the amount of supported traffic over a geographical area.

Massive MIMO is a key component for improving 5G data volume. The goal of PoC 11 [Fle62] is to demonstrate a feasible all-digital transmitter approach on a small scale with eight transmit branches, and to complete one chain with the required amplification stage. Instead of realizing multiple independent RF chain, the single-chip solution proposed in PoC 11, for massive numbers of transceivers using conventional RF circuitry, allows one to exploit duplication and parallelization in the digital domain, which is not a problem. This is a huge motivation for an all-digital transmitter: generating the RF signal in digital processing unit by purely digital means. In a massive-MIMO architecture, such a device could provide a higher number of RF signals than a traditional solution with multiple independent RF chains.

Table 3-9: Table of Use Cases for MDV KPI

Use case	High level MDV requirements	Addressed technology components	PoC/WP	Achieved result
Crowded venues	DL: 0.75 Tbps/km² UL: 1.5 Tbps/km²	Full duplex operation, (Category B)	5 / -	50% of MDV gain respect a TDD configuration
		Massive MIMO operation	11 / -	67.4 Gbps/km²
Dynamic Hotspot	DL: 750 Gbps/km² UL: 125 Gbps/km²	Multi Band Operation	4 / -	5.05 Gbps/km²
		Full duplex operation, (Category B)	5 / -	50% of MDV gain respect a TDD configuration
		Massive MIMO operation (Category B)	11 / -	9.63 Gbps/km²
50 + Everiwhere	Far remote rural: 500 Mbps/km² Rural: 5 Gbps/km² Suburban: 25 Gbps/km²	Multi Band Operation (Category B)	4 / -	0.581 Gbps/km²
		Virtualized processing at the edge (Category C)	9 / -	4x5Mhz (1 VeNB per physical core) 2x10MHz (1 VeNB per pair of physical cores)
		Massive MIMO operation (Category B)	11 / -	4.49 Gbps/km²
Mobile BB in a Vehicle	Urban: 150 Gbps/km² Suburban: 50 Gbps/km² Highway: 25 Gbps/km²	Multi Band Operation (Category B)	4 / -	5.05 Gbps/km²

For the computation of the contribution to MDV of the different technology components, the approach described in Section 5 (Annex A) has been used. In particular, starting from equation (1) in Section 5, legacy 4G network nodes support:

$$\mathrm{n_{MIMO}} = 2$$
$$\Delta\mathrm{B} = 20\ \mathrm{MHz\ x\ 3CC}$$

Current typical network configurations support 2 layer and up to 3 Component Carrier (CC) on Macro Layer. Exploiting simultaneously the Multi Band (PoC 4) and Massive MIMO (PoC 11) operation it is possible to achieve the values:

$$n_{MIMO} = 8$$

$$\Delta B = 120\ MHz$$

Taking into account the Macro Layer deployment where an average spectral efficiency could be around $\varepsilon = 5.5$, we can obtain:

$$\mathrm{R_{SotA}} = 427\ \mathrm{Mbps}$$
$$\mathrm{R} = 3.4\ \mathrm{Gbps}$$

Where $\mathrm{R_{SotA}}$ represents the SotA of the peak rate in a 4G Network, while R could be a promising rate for a 5G Macro Node. Based on the information in Table A.7 in [Itu13a], the Macro cell area in dense urban scenario is typically 0.1 km^2. Using relation (2) in Section 5, we can obtain that the MDV for the SotA is $\mathrm{MDV_{SotA}} = 4.27\mathrm{Gbps/km^2}$ while $\mathrm{MDV} = 34\ \mathrm{Gbps/km^2}$ is obtained exploiting the increment of the operational bandwidth and the Massive MIMO architecture. The obtained value is anyway distant from what is proposed as target in Table 3-9, but the MDV values shown for Crowded Venues and Dynamic Hotspot use cases can be achieved only exploiting a heterogeneous deployment of Macro layer in combination with Micro/Pico layer (where A is a value below 0.07 km^2).

Finally, the introduction of full-duplex operations can theoretically improve by 50 % the amount of band usable in order to support a higher MDV than the one computed previously.

Next, in the table below we detail the PoCs in which MDV KPI has been assessed.

Table 3-10: Table of PoCs addressing MDV KPI

PoCs	MDV content targets	Achieved result
4	For the DS1 model, an OBW of 120 MHz is considered.	5.05/0.581/5.05 Gbps/km^2 respectively for use cases DH, 50+ and BV
5	At least 50 % average MDV increase	50% of MDV gain respect a TDD configuration
9	The number of Base Band running in a Machine increases	For a given infrastructure deployment, the number of logical base station increases, which increases the density of the network increasing thus the MDV
11	For the DS3 model, the multi-antenna and MIMO capability increases the MDV	67.4/9.63/4.49 Gbps/km^2 respectively for use cases CV, DH and 50+

A high improvement of MDV KPI can be achieved taking into account the multiple technology components analyzed in Flex5Gware and listed in Table 3-10. MDV target described in the use cases like Crowded Venue and Dynamic Hotspot is challengingly high, but it can be obtained only where a densification of the network is introduced in conjunction with the technology components proposed in Flex5Gware. The process of virtualization of the Base Band, described in PoC 9, provides an easy and cheaper way to increase the density of the network nodes deployable by an operator. This is possible because the same general-purpose hardware can be used to run a higher number of cells.
A detailed analysis of the supported MDV, however, depends on the propagation scenario. This type of analysis can be addressed only using system-level simulations that have not been carried out within Flex5Gware. A preliminary back-of-the-envelope computation is only provided here.

3.2.6 NoU: Number of Users

The number of users (NoU) refers to the number of devices that are connected to the network. The 5G network will support new use cases, such as Smart Cities scenarios, where the number of devices could be challengingly high, or Crowded Venue scenarios, where the network has to handle a high number of users assembled in a confined space such as a stadium or a big plaza. These scenarios request an improvement of performance with respect to today's 4G networks. The NoU to be supported depends on the use case analyzed, as described in Table 3-11. Additional details can be found in [Fle11].
In Table 3-11 a list of technology components is associated to each Use Case. The technology components shown therein are the most promising to improve the NoU handled in a radio access network.

The antenna design for large bandwidth at mm-wave is analyzed in PoC 2 [Fle62], where an active antenna is co-designed focusing on the realization of a Substrate-Integrated-Waveguide (SIW) cavity-backed slot antenna, which is directly integrated with a power amplifier. This solution will reduce the device cost in order to cover the demands of the Smart Cities scenarios for a higher number of low-cost devices. Therefore, the aim of this PoC is to develop an active antenna system consisting of a low-cost planar antenna and a high-performance power amplifier. This full-wave/circuit co-design proposed in PoC 2 will exhibit benefits in terms of bandwidth, allowing the system to support a higher number of these devices capable of transmitting/receiving more efficienctly.

The multiband operation is described in PoC 4 [Fle62]. This technology component exploits the broadband and multiband capabilities of components to realize transceiver chains which support concurrent operation in multiple radio bands. This allows the hardware complexity to be reduced by decreasing the number of implemented transceivers in order to support multi operational bands. The increase of operational bandwidth is a key component to support the increase of users/devices that needs to be handled in the majority of the Use Cases.

Similarly as in the previous case with mobile data volume, Massive MIMO is also a key component of 5G to improve the number of users/devices handled in the radio access network, by exploiting the spatial diversity to serve multiple users/devices in the same time/frequency resources. Consequently, the explanation provided in the previous section for PoC 11 [Fle62] is also valid here.

Table 3-11: Table of Use Cases for NoU KPI

Use case	High level NoU requirements	Addressed technology components	PoC/WP	Achieved result
Crowded venues	A peak of 150000 users/km^2 can be supported.	Multi Band Operation (Category C)	4 / -	12000 users/km^2
		Massive MIMO operation	11 / -	1350 users/km^2
Dynamic Hotspot	200-2500 users/km^2 (Similar to 4G network)	Multi Band Operation	4 / -	200 users/km^2

Smart Cities	1.000 IoT devices per km^2 in cities in addition to regular users.	Antenna design providing a large bandwidth at mm-wave frequencies (Category C)	2 / -	This significantly large operational bandwidth also allows serving a large number of connected users
Perf. equipment	Billions of users.	Antenna design providing a large bandwidth at mm-wave frequencies (Category C)	2 / -	This significantly large operational bandwidth also allows serving a large number of connected users
Mobile BB in a Vehicle	Urban: 1000-3000 vehicles/km^2 Suburban: 500-1000 vehicles/km^2 Highway: 100-500 vehicles/km^2	Multi Band Operation (Category B)	4 / -	1000 vehicles/km^2

Similarly to what has been done in the previous subsection, the approach described in Section 5 (Annex A) has been used. to evaluate the NoU KPI of the different technology components. From the combination of (2) and (3) in Section 5, it is easy to see that we can define NoU as the rate between the cell throughput (R) and the product of the User throughput (R_U) times the Area (A):

$$\mathrm{NoU} = \frac{\mathrm{R}}{R_U \cdot \mathrm{A}}$$

Observing the KPI targets set in Section 3.2.9 for User Data Rate (UDR) we can consider for the Dynamic Hotspot use case an average value of downlink user throughput of $R_U = 300\ Mbps$. This means that the SotA configuration guarantees a $\mathrm{NoU_{SotA}} \cong 14$, while $\mathrm{NoU} \cong 113$ is obtained by exploiting the increased the operational bandwidth and the Massive-MIMO architecture. The introduction of the technical components proposed in Flex5Gware allows a sizable improvement of the number of simultaneously connected users handled by the Macro Layer. Exploiting mmWave in a denser cell deployment will further increase the number of devices supported by a 5G network, thus achieving the NoU values shown in Table 3-11.

Next, in the table below we detail the PoCs in which the NoU KPI has been assessed.

Table 3-12: Table of PoCs addressing NoU KPI

PoCs	NoU content targets	Achieved result
2	Targeted data rate in the order of Gbps for the CMOS PA	The supported 1.9 GHz of operational bandwidth allows serving a large number of connected users

4	Calculated for DS1 for different UDR requirements of each use case	12000/200/1000 users/km^2 respectively for use cases CV, DH and BV
11	Calculated for DS3 for 50 Mbps UDR (target value)	1350 users/km^2

Based on the results shown in this section, we can summarize that the increase in the NoU is achieved by exploiting the technology components listed in Table 3-12, but it is not possible to evaluate the overall gain (quantified as Number of Users/Devices handled) in a commercial network which supports multiple overlapping layers of Macro/Micro Cell in outdoor and indoor deployments.

3.2.7 BW: Bandwidth

This KPI is related to the bandwidth supported by both network nodes and UE/sensors/actuators. This KPI has two distinct facets: the radio bandwidth (RBW) describes the full RF bandwidth received or transmitted by a radio unit, whereas the operational bandwidth (OBW) refers to the sum of all used channels inside the radio bandwidth. Generally speaking, Flex5Gware addresses the BW KPI differently, depending on whether the target bands are below or above 6 GHz. For bands below 6 GHz, the main issue is that, due to the fact that the available spectrum is scarce and sparse, 5G transceivers will need to be able to extract the maximum spectrum efficiency by, e.g., having multiband capabilities and aggregate the spectrum coming from different bands to increase the OBW, or by having full-duplex capabilities. For bands above 6 GHz, the available spectrum is significantly larger and, in this case, the most important aspect for platforms operating at these frequencies is to be able to use the largest RBW possible.

As indicated in the following tables, Flex5Gware addresses aspects related to the BW KPI by enabling high-bandwidth operation at mmWave (PoC 1 presents a BW tuning range of 7.9 GHz and PoC 2 showcases a bandwidth of 1.9 GHz for the joint antenna and PA) and, for bands below 6 GHz, by demonstrating the viability of multiband and full-duplex transceivers.

Table 3-13: Table of Use Cases for BW KPI

Use case	High level BW requirements	Addressed technology components	PoC/WP	Achieved result
Crowded venues	UL: 3 GHz, DL: 1.5 GHz	Operation over a wide frequency range	1 / -	7.9 GHz of tuning range, which is enough to cover the BW requirements.
		Full duplex operation (BW reuse)	5 / -	20 MHz signal bandwidth (for demonstration purposes), but concept applicable to larger bandwidths as well

Dynamic hotspots	From 100 MHz to 1 GHz	Operation over a wide frequency range	1 / -	7.9 GHz of tuning range, which is enough to cover the BW requirements.
		Multiband operation (OBW = 120 MHz)	4 / -	6x20 MHz inter-band CA in three radio bands
Perf. equipment	100 MHz (OBW)	Operation over a wide frequency range	1 / -	7.9 GHz of tuning range, which is enough to cover the BW requirements.
		Large operation bandwidths	2 / -	The measured bandwidth (BW) for the integrated prototype amounts to 1.9 GHz
50+ everywhere	Availability of a mode with a bandwidth equal to or greater than 50 MHz	Large operation bandwidths	2 / -	The measured bandwidth (BW) for the integrated prototype amounts to 1.9 GHz
		Multiband operation (OBW = 120 MHz)	4 / -	6x20 MHz inter-band CA in three radio bands

Next, in the table below we detail the PoCs in which BW KPI has been assessed.

Table 3-14: Table of PoCs that address BW KPI

PoCs	BW content targets	Achieved result
1	Demonstrated by mmWave implementation: tuning range (GHz).	Tuning capacity between 23.3-31.2 GHz for the 28 GHz PLL, which represents a tuning range of 7.9 GHz. The BW is not directly limited by PLL, but the PLL should have enough tuning range to cover full BW.
2	Achieved BW of the integrated antenna and PA	The measured bandwidth (RBW) for the integrated prototype amounts to 1.9 GHz
4	Up to 120 MHz (6x20 MHz) for bands below 6 GHz	6x20 MHz inter-band CA in three radio bands
5	Bandwidth of the Full-Duplex transceiver implementation	20 MHz signal bandwidth

Based on the results presented in the previous tables, it seems clear that BW is a KPI for which satisfactory results have been obtained for all the use cases in which it was relevant. In addition, four PoCs out of eleven addressed the BW KPI, which places this KPI in the mid-range as far as Flex5Gware impact is concerned.

3.2.8 LAT: Latency

The latency KPI refers to the delay experienced by a given unit of information when transversing a given part of the network. In this way, the “end-to-end” latency refers to the time elapsed since a frame is transmitted at one side of the network until it reaches the other side (these two being reference points), while “round-trip time” accounts for the delay between the transmission of a request and the successful reception of the corresponding reply at the same point.

Flex5Gware addresses improvements in LAT in two complementary ways. On the one hand, by developing novel technologies that are capable of processing data at higher speeds, such as very fast A/D, D/A converters. By using digital beamforming with low-resolution ADC, the overhead, hence the latency, of the constant beam alignment required by hybrid beamforming can be saved. On the other hand, thanks to the flexibility, versatility and re-configurability of the architecture, by adapting the configuration of the communication elements and adapting to scenario variations. For instance, the MAC layer may use a scheme without ARQ when conditions are near-optimal (minimum LAT), and move to more complex schemes when guarantees are to be provided.

In Table 3-15 we list the technology components related to the LAT KPI that are associated with each considered Use Case, whenever applicable.

Table 3-15: Table of Use Cases for LAT KPI

Use case	High level LAT requirements	Addressed technology components	PoC/WP	Achieved result
Crowded venues	The most critical issue is the sharing of real-time HD videos. 10 ms for 2-way RAN (up to 50 ms when # users is huge)	mmWave digital beamforming with low resolution ADCs	- / 3	As shown in [Bar15] can reduce the connection setup time by several ms. By avoiding the constant tracking of the beam some slots in a frame can also be saved.
Dynamic hotspots	10 ms (End to End latency is not critical in this case)	mmWave digital beamforming with low resolution ADCs	- / 3	As shown in [Bar15] can reduce the connection setup time by serval ms. By avoiding the constant tracking of the beam some slots in a frame can also be saved.
Smart Cities	Up to 1 minute on low priority IoT applications (such as environmental monitoring) and less than 5 seconds on high priority (i.e. people detection		8 / -	Devices developed to perform environmental monitoring employed in PoC 8 show their data requires a negligible time to go through the network.

Perf. equipment	150 µs from antenna to processed data	No technology addressed this UC/KPI combination	- / -	No results are available.
Vehicle 2x	10 ms for automated operation (signaling), 50 ms for real-time streaming	Ability to change between RAT technologies and adapt their behavior	8 / -	802.11aa mechanisms can ensure multicast delivery at low delay, e.g. UR=2 incurs in approx. three transmissions (less than 2 ms even at 24 Mbps) [Fle52]
		Configure the HW/SW split and their parameters	7 / -	Adjusting the configuration results in up to 44% reduction in latency [Fle42] at an increased cost in resource consumption.

Next, in Table 3-16 below we detail the PoCs in which LAT KPI has been assessed.

Table 3-16: Table of PoCs addressing LAT KPI

PoCs	LAT content targets	Achieved result
7	The use of different HW/SW partitions results in different trade-offs in terms of resource consumption and performance. The obtained latency figures will be matched against those maximum values in the different functional splits recommended by the Small Cell Forum (which range from hundreds of microseconds to tens of miliseconds, depending on the split)	The total latency for the 20 MHz with NETCFG2 is approximately 12 ms [Fle42], with the L1 latency being approximately 1 ms, thus supporting the MAC-PHY and Split MAC splits defined by the Small Cell Forum [Scf15].
8	The ability to select and configure the most appropriate RAT and MAC technology to adapt to network conditions guarantees minimization of the delay.	The implemented RAT selection procedures are practically immediate (wpa_supplicant is bypassed). Dynamic BW switching can be perfomed in less than 200 us [Fle52],

The PoCs demonstrate the ability of Flex5Gware prototypes to support different LAT requirements by adjusting the HW/SW partitioning accordingly. This way, the demonstrated capabilities will not feature novel mechanisms or technologies to reduce the LAT, but instead the ability to optimize other performance metric while committing to LAT requirements.

3.2.9 UDR: User Data Rate

The UDR KPI is related to the expected gains in terms of user data rate in 5G networks when compared to 4G. Together with the FVR and NRG KPIs described above in Sections 3.2.1 and 3.2.3, the UDR KPI is one of the project KPIs for which Flex5Gware has provided more results. In particular, seven PoCs out of eleven address this KPI.

This KPI relates to the achieved end-user (e.g., handheld for human traffic, device for MTC, etc.) data rates (both UL and DL). In particular, Flex5Gware has contributed to the increase of the user data rate by: i) increasing the user data rate per spectrum unit via full-duplex operation (PoC 5) and faster FEC decoding architectures (PoC 6); ii) increasing the user bandwidth via multi-band operation (PoC 4) and the operation at mmWave bands (PoC 2), and iii) reducing the experienced interference through dynamic basestation coordination (PoC 10) and reconfiguration (PoC 7), and also via massive MIMO transmissions (PoC 11).

Table 3-17: Table of Use Cases for UDR KPI

Use case	High level UDR requirements	Addressed technology components	PoC/WP	Achieved result
Crowded venues	DL: 25 Mbps, UL: 50 Mbps	Full duplex operation (Category B)	5 / -	50 % improvement in achieved rates for a given bandwidth.
		High-throughput low-power LDPC decoder	6 / -	Achieved rates up to 4.1 Gbps for the decoder architecture.
		Massive MIMO operation (Category C)	11 / -	50 Mbps can be achieved for DS3 conditions (CV use case)
Dynamic hotspots	DL: 300 Mbps, UL: 50 Mbps	Full duplex operation (Category B)	5 / -	50 % improvement in achieved rates for a given bandwidth.
		High-throughput low-power LDPC decoder	6 / -	Achieved rates up to 4.1 Gbps for the decoder architecture.
		Flexible HW/SW partitioning	7 / -	Rates of up to 68 Mbps can be achieved in 20 MHz BW. With carrier aggregation the 300 Mbps target could be achieved.
		Global scheduling algorithm (CoMP)	10 / -	Around 10 - 25 % UDR gains thanks to coordinated scheduling.

Perf. equipment	10 Gbps (specific scenarios), 100 Mbps (urban areas), 50 Mbps (everywhere)	Large operation bandwidths	2 / -	The user data rate amounts to 5.18 Gbps for a cell size of 0.01 km2 and 1.67 Gbps for a cell size of 0.031 km2.
		Estimated UDR for different building blocks developed in WP2	- / 2	1.6 Gbps can be achieved thanks to the low noise 28 GHz PLL architecture. 6 Gbps can be achieved by the 28 GHz CMOS PA, and 5.1 Gbps by the K-band PA. 112 Mbps achieved by antenna working at bands below 6 GHz.
50+ everywhere	DL: 50 Mbps (100 Mbps, if possible), UL: 25 Mbps	Global scheduling algorithm (CoMP)	10 / -	Around 10 - 25 % UDR gains thanks to coordinated scheduling with protection to cell edge users. With 10 MHz of bandwidth the target is already achieved.
Mobile BB in vehicles	DL: 50 Mbps (Instantaneous), 5 Mbps (operation)	High operational bandwidth	4 / -	5.05 Mbps achieved for broadband in vehicles use case.
		Optimized video transmissions	- / 5	Achieved rates between 5 and 36 Mbps for video transmission (usable in vehicular environments)
Vehicle 2 X	See-through: 10 Mbps, Intersections: 40 Mbps	Optimized video transmissions	- / 5	Achieved rates between 5 and 36 Mbps for video transmission (usable in vehicular environments)

Next, in the table below we detail the PoCs in which UDR KPI has been assessed.

Table 3-18: Table of PoCs that address UDR KPI

PoCs	UDR content targets	Achieved result
2	The user data rate (UDR) is calculated based on the achieved 2 GHz stand-alone antenna impedance bandwidth, a transmission power of 10 dBm and a target of 1000 users/km2	The user data rate amounts to 5.18 Gbps for a cell size of 0.01 km2 and 1.67 Gbps for a cell size of 0.031 km2.
4	Achieved UDR computed based on DS1	5.05 Mbps achieved for broadband in vehicles use case.

5	At least 50 % average data rate increase compared to a TDD system is expected from the technology	85-90 dB of cancellation achieved, which guarantees the expected 50 % increase in the achievable rates for a given bandwidth.
6	Data rates between 1.2 to 2.7 Gbps	Achieved rates up to 4.1 Gbps for the decoder architecture.
7	For the DL, there is a transmission mode that supports more than 50 Mbps	Rates of up to 68 Mbps can be achieved in 20 MHz BW
10	Gains in UDR are foreseen thanks to the scheduling algorithms	Around 10 - 25 % gains depending on the load conditions, with special protection of cell edge users. Rates of up to 11 Mbps per RB can be achieved (simulations).
11	UDR derived from bandwidth and DS3 conditions	50 Mbps for DS3 conditions [Fle22].

Based on the results presented in the previous tables, it seems clear that the UDR is a KPI for which satisfactory results have been obtained for all the use cases in which UDR was relevant. The only case for which the KPI targets are not fully met would be for one of the special cases of the Performance Equipment use case in which data rates of up to 10 Gbps could be expected (under very specific circumstances) and Flex5Gware PoCs have demonstrated 5.18 Gbps. In addition, seven out of eleven PoCs addressed the UDR KPI, which places this KPI in the top-range in terms of the impact that Flex5Gware has had on it.

3.2.10 ISF: Integration, Size, Footprint

This KPI represents the level of integration, HW size, volume and footprint. It also covers the HW footprint related to the SW design implications on the digital HW. The requirements are expressed in relative terms compared to 4G, for the footprint, and SotA technology, for the size/volume and level of integration. The reference values for ISF are reported in Table 3-19 on the basis of the Use Cases where this KPI is more relevant. In addition, the table shows the most promising technology components to improve ISF associated to each Use Case.

Co-integration of PA and antennas is described in PoC 2 and this technology component has the objective to reduce the antenna physical footprint compared to LTE combined with an increase in the level of integration of the PA to allow a co-location with the antenna. This is very important because the number of antennas (respectively PAs), in base stations and terminals has been increasing and the impact in installation costs, visual impact and terminal sizes have to remain strictly bounded.

Dynamic HW/SW partitioning is described in PoC 8, and this technology component has the objective to introduce reconfigurability in the radio behavior by allowing to dynamically allocate HW resources depending on the communications context. This allows one to optimally utilize the HW available and potentially reduce the use of specific HW blocks. One example is shown in Table 3-19, where, for the Smart cities use case, an average reduction in memory utilization is achieved by offloading functions to HW.

Low-cost, high-volume CMOS technology is described in PoC 1 and this technology component has the objective of achieving a fully integrated solution for a frequency synthetizer, but at a much higher frequency than the ones found in 4G. This enables the integration of many transceiver chains in a massive-MIMO implementation, which increases the area efficiency.

Table 3-19: Table of Use Cases for ISF KPI

Use case	High level ISF requirements	Addressed technology components	PoC/WP	Achieved result
Smart cities	1.5x reduction of the size of electronic boards and sensors so as to minimize the installation costs and visual impact of nodes deployed.	Co-integration of PA and antennas	2 / -	Antenna physical footprint reduced by a factor of 25 compared to LTE antennas, achieving a size of 1x1 cm^2. PA integration in 40nm CMOS process has also very small footprint allowing integration with the antenna.
		Dynamic HW/SW partitioning	8 / -	Average Reduction by 53.27% in terms of SW memory utilization, when performing reconfiguration targeting improved performance (more functions executed in HW)
Perf. equipment	Same physical footprint and BOM cost compared to 4G high performance devices today	Low cost, high volume CMOS technology	1 / -	Fully integrated solutions have been demonstrated using the same level of integration as seen for 4G, but at much higher frequencies. The technology used is a standard commercial process node already in volume production.
		Co-integration of PA and antenas	2 / -	Antenna physical footprint reduced by a factor of 25 compared to LTE antennas, achieving a size of 1x1 cm^2. PA integration in 40nm CMOS process has also very small footprint allowing integration with the antenna.

Next, in the table below we detail the PoCs in which ISF KPI has been assessed.

Table 3-20: Table of PoCs that address ISF KPI

PoCs	ISF content targets	Achieved result
1	CMOS is selected as a low-cost option for high integration level. The frequency synthesizer must be area efficient to enable integration of many transceiver chains in a massive MIMO implementation.	The synthesizer footprint is competitive to reported SotA given the advanced technology node. Chip area: ~ 0.2 mm^2 for 28 GHz as expected ~ 1 mm^2 for 60 GHz as expected Core area: ~ 0.016 mm^2 for 60 GHz as expected
2	Small dimensions of mmWave wavelength allows for the realization of small footprint antennas (order of 1x1 cm^2). Antenna on low profile substrate (250 µm). Compact HW due to co-design	Antenna physical footprint reduced by a factor of 25 compared to LTE antennas, achieving a size of 1x1 cm^2. PA integration in 40nm CMOS process has also very small footprint allowing integration with the antenna.
8	As some computational tasks are offloaded to sensors, the overall SW memory utilization on 5G nodes can be reduced	Average Reduction by around 50 % in terms of SW memory utilization, when performing reconfiguration targeting improved performance (more functions executed in HW)

An assessment of Table 3-19 and Table 3-20 allows us to say that the target results have been achieved, or even exceeded, for the Integration/Size/Footprint (ISF) KPI. For the Smart Cities use case, all technology components have fulfilled the expectation to reduce by at least 1.5 times the size of the HW and, for the Performance Equipment use case, all technology components have a maximum size equal to the corresponding 4G technology.

In the following section, an overall analysis of the achieved KPI results is provided together with the conclusions of the project.

3.3 Result summary

Table 3-21 provides a summary of the Flex5Gware KPI fulfilment. We are only considering building blocks developed inside the project, and how these relate each specific KPI. The end-to-end system KPI fulfilment is outside the project scope, but has been addressed in cross project 5G-PPP workshops.

Table 3-21: Summary of KPI achievements for each Flex5Gware use case

The KPI figures refer only to the performance achieved considering building blocks developed in Flex5Gware - not the full end-to-end system							
KPI\UC	**CV**	**DH**	**SC**	**PE**	**50+**	**MBV**	**V2X**
FVR	< 30 s [PoC 1,4,5]	< 300 s [PoC 1,4,5,7,8,9,10,11]	< 30 s [PoC 8]		Multiband operation [PoC 4,10]	Capability to adapt to fast varying radio conditions, and to activate other RATs [PoC 4]	
CST			1.5x reduction [PoC 2]	Same BOM cost compared to 4G high performance devices today [PoC 1,2,6]			
NRG		From 40 % to 60 % reduction [PoC 6,7,8,9,10]	1-2 years batteries [PoC 2,3,8 and WP 5]	3 days batteries (smart phones) More than 10 days (less performing devices) [PoC 1,2,3]	From 25 % to 60 % reduction [PoC 2,3,10]		
RES	95 % [WP 5]	95 % [WP 5]	Power and communication backup modes [WP 5]	99.999 %	MIMO operation [PoC 11]		99.999 % (automated operation) 99.9 % (status updates) [PoC 8]
MDV	DL: 3.75 Tbps/km² UL: 7.5 Tbps/km² [PoC 5]	DL: 750 Gbps/km² UL: 125 Gbps/km² [PoC 4,5,11]			Far remote rural: 500 Mbps/km² Rural: 5 Gbps/km² Suburban: 25 Gbps/km² [PoC 4,9,11]	Urban: 150 Gbps/km² Suburban: 50 Gbps/km² Highway: 25 Gbps/km² [PoC 4]	
NoU	150000 users/km² [PoC 4,11]	200-2500 users/km² [PoC 4]	1000 IoT devices/km² [PoC 2]	Billions of users [PoC 2]		Urban: 1000-3000 veh/km² Suburban: 500-1000 veh/km² Highway: 100-500 veh/km² [PoC 4]	
BW	3 GHz UL 1.5 GHz DL [PoC 1,5]	From 100 MHz to 1 GHz [PoC 1,4]		100 MHz (OBW) [PoC 1,2]	≥ 50 MHz [PoC 2,4]		
LAT	10 ms [WP 3]	10 ms [WP 3]	< 60 s (low prio) < 5 s (high prio) [PoC 8]	150 µs from antenna to processed data			10 ms (automated operation) 50 ms (streaming) [PoC 7,8]
UDR	DL: 25 Mbps UL: 50 Mbps [PoC 5,6,11]	DL: 300 Mbps UL: 50 Mbps [PoC 5,6,7,10]		10 Gbps in specific scenarios 100 Mbps in urban areas 50 Mbps everywhere else [PoC 2, WP 2]	DL: 50 Mbps (100 Mbps, if possible) UL: 25 Mbps [PoC 10]	Instantaneous: 50 Mbps/veh (DL) Operation: 5 Mbps/veh (DL) [PoC 4, WP 5]	10 Mbps (see-through) 40 Mbps (intersections) [WP 5]
ISF			1.5x reduction [PoC 2,8]	Same physical footprint compared to 4G high performance devices today [PoC 1,2]			

The color code used in Table 3-21 is the following:

- Dark green: KPI target achieved by Flex5Gware results;
- Light green: Flex5Gware has made quantitative progress towards the achievement of the KPI, but the project contributions need to be complemented with other technologies to fully achieve the 5G KPI target;
- Yellow: Flex5Gware has made qualitative progress towards the achievement of the KPI, but the project contributions need to be complemented with other technologies to fully achieve the 5G KPI target;
- Red: Flex5Gware has not significantly contributed towards the achievement of this KPI. However, the KPI value set forth by Flex5Gware is still valid and further progress from some other initiatives will be required.

4. Conclusions

In order to summarize the level of achievement per KPI, the results in Table 3-21 have been processed qualitatively averaging over the use case dimension. The results are shown graphically in Figure 1, in which the color code is the same as defined before, but represents results averaged along the different use cases for which a given KPI is relevant.

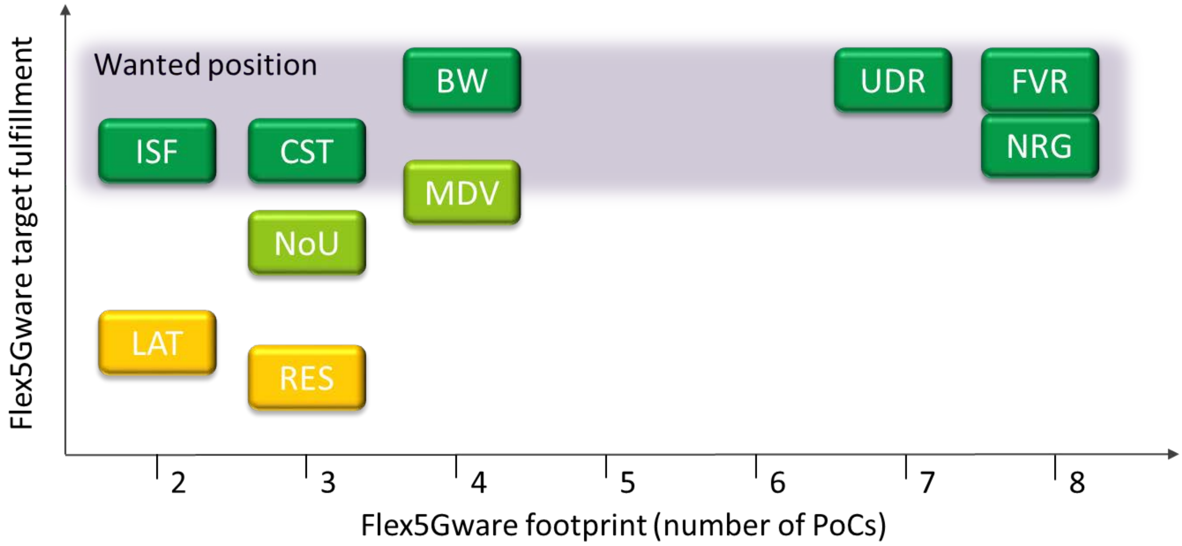

Figure 1: Summary of the Flex5Gware achievements in terms of KPI fulfilment

As it can be seen from the results reported in Section 3 and graphically summarized in Table 3-21 and Figure 1, Flex5Gware has made a remarkable progress towards the fulfilment of KPIs that will be required in 5G HW/SW platforms. Of course, being a 5G PPP Phase I project, it is not expected that Flex5Gware would provide technical solutions for all the challenges that are posed to 5G HW/SW platforms, but it is worth pointing out that the achieved results are consistent with the initial objectives set forth in Flex5Gware DoW.

In particular, the FVR, NRG, and UDR KPIs, which are the ones that have a larger footprint in the project and for which most positive results have been obtained, are at the core of the Flex5Gware aim. The overall objective of Flex5Gware has been to provide the building blocks that will facilitate the delivery of highly reconfigurable HW platforms (FVR) together with HW-agnostic SW platforms taking into account increased capacity (UDR), reduced energy footprint (NRG), as well as scalability and modularity (FVR), to enable a viable transition from 4G mobile wireless systems into 5G.

Moreover, significant progress and KPI fulfilment has been achieved for the BW, ISF and CST KPIs, which are also closely related to the low-level technology developments carried in out in Flex5Gware.

Finally, regarding KPIs that are more related to system-wide network metrics like RES, LAT, NoU, and MDV, the level of target fulfilment is more heterogeneous, but progress in all areas has been accomplished and reported on in the Flex5Gware work package deliverables.

The following figure, presents a graphical representation of the fulfilment level in terms of KPIs:

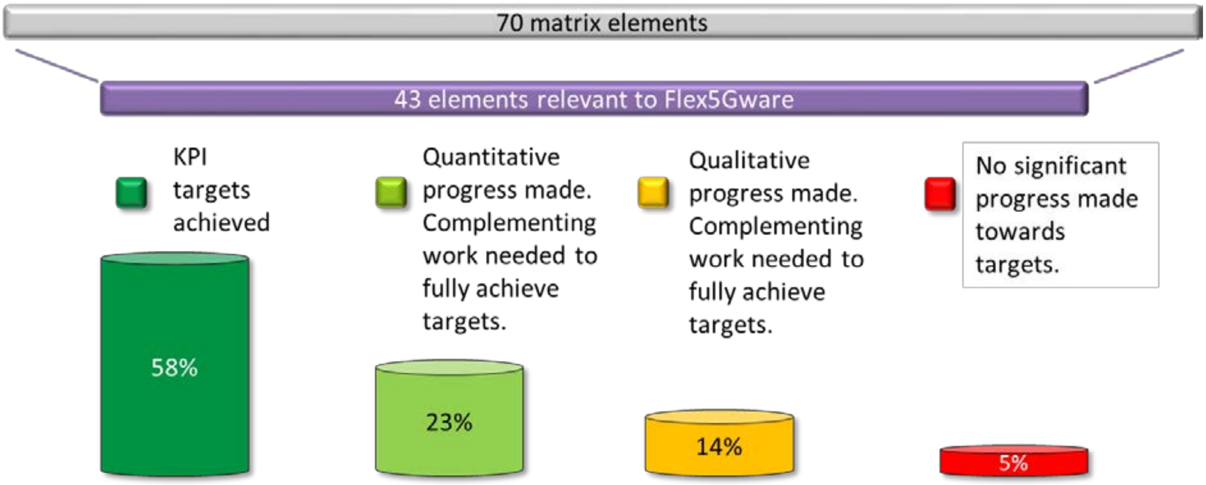

Figure 2: Percentages of Flex5Gware of KPI fulfilment

Finally, it should be noted that most of the KPI improvement achieved by Flex5Gware stems from experimental results extracted directly from the Flex5Gware PoCs. Clearly, this is a significant step towards the validation of the practical viability of the HW/SW platforms building blocks in comparison to situations where KPI fulfilment primarily is obtained via simulations or analytical results. Moreover, an accelerated exploitation of the Flex5Gware PoCs is outlined in [Fle72], which provides an accessible overview of the project outcome. This enables an efficient impact on future R&D activities.

5. Annex A – System model for category B KPI computation

As pointed out previously, the KPIs MDV and NoU are system-wide KPIs that are very difficult, if not impossible, to evaluate within the building blocks and PoCs developed in Flex5Gware. For example, the MDV KPI cannot be evaluated directly in a PoC because the requirement of involving a high number of both radio access points and users monitored inside a network, which is out of the scope of the Flex5Gware project. The same holds true for the NoU KPI.

In order to evaluate the capability of Flex5Gware building blocks to address the MDV and NoU values shown in Table 3-9, Table 3-10, Table 3-11, and Table 3-12, the improvement of the proposed technology components has to be estimated based on, e.g., a simple system-wide performance model.

Thus, and given that Flex5Gware belongs to the group of 5G PPP Phase I projects, the approach has been to use the results developed within the Metis-II project. According to this project (the section 3.2.5 in [Met23]), the peak data rate supported by a network node can be estimated by:

$$R = 0.648 \times \varepsilon \times n_{MIMO} \times \Delta B \quad (bps) \tag{1}$$

where ε is the spectral efficiency (which ranges among values from 4 to 7.3 according to [Itu13a], n_{MIMO} represents the number of parallel MIMO streams and ΔB represents the bandwidth in Hz.

Now, this given network node will have a coverage area denoted by A. Typical values for the cell area for km^2 can be estimated on the basis of information contained in Table A.7 in [Itu13a] where the cell area is provided as a function of the network node type (Macro Base Station, Micro Base Station, Pico Base Station or Hot Spot). The table is reproduced here for completeness:

TABLE A.7

Assumed cell area per radio environment (km^2) (with penetration loss)

Radio environment	Teledensity		
	Dense urban	Suburban	Rural
Macro cell	0.10	0.15	0.87
Micro cell	0.07	0.10	0.15
Pico cell	0.0016	0.0016	0.0016
Hot spot	0.000065	0.000065	0.000065

NOTE – Hot spots are geographically isolated from each other.

Thus, from the definition of MDV, this KPI can be straightforwardly expressed as the rate between cell throughput (R) and Area (A):

$$MDV = \frac{R}{A} \tag{2}$$

Finally, it is important to take into account that the cell area can be approximately related to the transmission power per carrier of the base station according to [Itu13a,Itu13b]:

- Macro: Radius range 200 m → 2 km, power range > 33 dBm
- Micro: Radius range 100 m → 200 m, power range 24 dBm → 33 dBm

- Pico: Radius range 20 m → 100 m, power range 20 dB → 24 dBm
- Hotspot: Radius range < 20 m, power range 10 dBm → 20 dBm

Thus, we have now obtained a method to relate the MDV KPI with low level parameters like the number of MIMO streams ($\mathrm{n_{MIMO}}$), the transceiver bandwidth (BW, $\Delta\mathrm{B}$) and the transceiver power (related to the cell coverage area). Despite this model may come across very simple, it is enough to capture the impact of the Flex5Gware developments into system level KPIs (like MDV).

As far as the NoU KPI is concerned, it can also be straightforwardly evaluated thanks to the simple relation between the number of users and the cell throughput:

$$\mathrm{MDV} = R_U \times \mathrm{NoU}\,, \quad (3)$$

where R_U can be assimilated to the UDR KPI as it represents the user data rate.

References

[Bar15] C. N. Barati et al., "Directional Cell Discovery in Millimeter Wave Cellular Networks," in IEEE Transactions on Wireless Communications, vol. 14, no. 12, pp. 6664-6678, Dec. 2015. doi: 10.1109/TWC.2015.2457921

[Cip14] FP7 CityPulse, M. Presser, L. Vestergaard, S. Ganea, Deliverable D.2.1: "SmartCity Use Cases and Requirements", May 2014.

[Elh15] R. El Hattachi, J. Erfanian, et al., "5G White Paper" by NGMN Alliance, available online: https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf, February 17th, 2015.

[Euc13] EU Commission and 5G-PPP contract. Available at: https://5g-ppp.eu/contract/. The technical annex is also available at: https://5g-ppp.eu/wp-content/uploads/2014/02/Advanced-5G-Network-Infrastructure-PPP-in-H2020_Final_November-2013.pdf

[Fet14] G. Fettweis, H Boche, et al., " The Tactile Internet", ITU-T Technology Watch Report, August 2014

[Fle11] Flex5Gware Project, "Deliverable 1.1: 5G system use cases, scenarios, and requirements break-down", December 2015.

[Fle22] Flex5Gware Project, "Deliverable 2.2: Analogue components for highly performant and versatile 5G RF front-ends", May 2017.

[Fle32] Flex5Gware Project, "Deliverable 3.2: Mixed-signal strategies for 5G: final architecture and design for flexibility, power and spectral efficiency", May 2017.

[Fle42] Flex5Gware Project, "Deliverable 4.2: Final report on HW architectures", May 2017.

[Fle52] Flex5Gware Project, "Deliverable 5.2: Performance evaluation", May 2017.

[Fle61] Flex5Gware Project, "Deliverable 6.1: Preliminary PoC evaluation in Flex5Gware", June 2016.

[Fle62] Flex5Gware Project, "Deliverable 6.2: Final PoC avalueation in Flex5Gware", June 2017.

[Fle72] Flex5Gware Project, "Deliverable 7.2: Dissemination and standardization activities. Technology and exploitation roadmaps", June 2017.

[Itu13a] Report ITU-R M.2290-0 (12/2013), "Future spectrum requirements estimate for terrestrial IMT

[Itu13b] Report ITU-R M.2292-0 (12/2013), "Characteristics of terrestrial IMT-Advanced systems for frequency sharing/interference analyses

[Scf15] "Small Cell Virtualization Functional Splits and Use Cases", Small Cell Forum Release 5.1 (159.05.1.01), June 2015

[Met23] Metis-II Project, "Deliverable 2.3: Performance evaluation results", February 2017.

[Wul05] D. Wulich, "Definition of Efficient PAPR in OFDM," IEEE Comm. Let., vol. 9, no.9, pp. 832-834, Sept. 2005.

http://www.flex5gware.eu